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A Realistic FDTD Numerical Modelling Framework of Ground Penetrating Radar for Landmine Detection

Iraklis Giannakis, Antonios Giannopoulos and Craig Warren

Abstract—A 3D finite-difference time-domain (FDTD) algorithm is used in order to simulate ground penetrating radar (GPR) for landmine detection. Two bowtie GPR transducers are chosen for the simulations and two widely employed anti-personnel (AP) landmines, namely PMA-1 and PMN are used. The validity of the modelled antennas and landmines are tested through a comparison between numerical and laboratory measurements. The modelled AP landmines are buried in a realistically simulated soil. The geometrical characteristics of soil's inhomogeneity are modelled using fractal correlated noise which gives rise to Gaussian semivariograms often encountered in the field. Fractals are also employed in order to simulate the roughness of the soil's surface. A frequency dependent complex electrical permittivity model is used for the dielectric properties of the soil, which relates both the velocity and the attenuation of the electromagnetic waves with the soil's bulk density, sand particles density, clay fraction, sand fraction and volumetric water fraction. Debye functions are employed to simulate this complex electrical permittivity. Background features like vegetation and water puddles are also included in the models and it is shown that they can affect the performance of GPR at frequencies used for landmine detection (0.5-3 GHz). It is envisaged that this modelling framework would be useful as a testbed for developing novel GPR signal processing and interpretations procedures and some preliminary results from using it in such a way are presented.

Index Terms—Antennas, anti-personnel landmines, bowtie, dispersive, FDTD, fractals, GPR, GprMax, grass, modelling, roots, rough surface, vegetation, water puddles.

I. INTRODUCTION

NUMEROUS demining methods have been suggested over the years, from the most common and one of the first humanitarian demining methods used, the metal detector [1]–[3] to trained dogs, trained rats [4], chemical methods, nuclear methods [1], [5] and geophysical methods like acoustic/seismic [5], [6] and electrical resistivity techniques [7], [8].

Ground penetrating radar (GPR) has a wide range of applications [9] and it has been extensively used for landmine detection [10]. The ability to detect plastic landmines and the greater depth range, compared with metal detectors in dry environments with no clay or saturated soils, are some of the reasons why GPR is considered as an attractive demining method [10].

A better understanding of the scattering mechanisms within the ground can help us increase the effectiveness of GPR

and investigate its limitations. This can be achieved through numerical modelling that can provide insight on how the soil's characteristics can influence the overall performance of GPR. Apart from that, numerical modelling can be a practical tool for testing and comparing different antennas and processing algorithms in a wide range of environments. Further, a realistic numerical model can be also employed for training purposes in machine learning based approaches. In order to address a multi-variable problem like GPR demining using a machine learning approach, will require a large number of data from a diverse set of scenarios [11]. A reasonable and viable approach to obtain a diverse, equally distributed and adequately large dataset is through a realistic numerical modelling framework that faithfully represents the GPR forward problem.

Maxwell's equations, that are the governing equations of the GPR forward problem, can be numerically solved using a variety of methods, amongst them the finite element method, the method of moments [12], implicit finite-difference techniques (Crank-Nicolson method [13], alternative-direction implicit [14]), transmission line matrix [12] and others. The finite-difference time-domain (FDTD) method [15], [16] first introduced by Yee [19], is considered to be a very attractive choice for a number of reasons [12], [17] the most important of which are its computational efficiency and its time domain nature that particularly suits the GPR problem. We use gprMax [18], a free software that numerically solves Maxwell's equations by using a second order FDTD algorithm.

Numerical modelling of GPR is considered to be an alternative interpretation approach [17] and has been extensively applied to a number of GPR applications, amongst them are: the detection of dense non aqueous phase liquids (DNAPL) [20], [21], the detection of geological targets like faults and caves [22], [23], for tunnel inspections [24], detecting and assessing pipes [25], in the inspection and condition assessment of bridges [26], [27], for forensic applications [28], mineral exploration [29] and airborne GPR [30]. In the case of GPR numerical modelling for landmine detection, generic types of antennas over simple targets buried in both homogenous and inhomogeneous soils have been modelled by [31]–[34]. More advanced and realistic models for both antennas and targets are employed by [35]–[37] in order to simulate single GPR traces (A-Scans) which were subsequently used as a reference in an attempt to discriminate between landmines and false alarm targets.

As stated in [10] a lot of GPR antennas were validated in ideal conditions but their performance in real complex

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environments was found to differ significantly from the predicted one. Although, the probability of detection (PD) can reach near 100% and the probability of false alarm (PFA) fall to near 0.01% at simple test sites, in realistic conditions PD can fall to 50% and PFA can reach to 10% [10]. Based on that, numerical modelling should be able to simulate and capture the behaviour of GPR in realistic and appropriately complex environments and not only in clinically simplified ones. Such simplifications give rise to predictable results that cannot then be used to validate the performance of GPR in realistic conditions. Landmines can be found in a number of different environments, namely, desert, jungle, urban settings and others [10]. The proposed numerical modelling framework is here explicitly applied to rural environments. Arid as well as tropical environments can be accurately modelled using the suggested approach by simple modifications of input parameters.

One of the most challenging problems regarding the numerical modelling of GPR is how to accurately implement the dielectric properties of the soil, *i.e.* its frequency dependent electrical permittivity. Simplistic models based on a constant permittivity with a conductive term cannot accurately describe the soil's behaviour for frequencies employed in demining. Dielectric properties of soils is a multi-parametric problem and an analytical and completely inclusive function to describe them has yet to be derived.

A lot of soils and rocks can be accurately simulated employing either a Cole-Cole function [38]–[40], a constant Q factor [41]–[43] or the more inclusive Jonscher function that holds as a special case the constant Q factor approach [44]. Both the Cole-Cole and Jonscher functions cannot be directly implemented into an FDTD code. Approximations to these functions with multi-Debye relaxations [45]–[47] is the most usual approach for implementing these type of dielectric properties into FDTD. Numerically evaluated fractional derivatives [48] as well as Pade approximations [49] have been also suggested for implementing complex dielectric properties. Multi-Debye expansions however, are more computationally efficient because it is straightforward to choose the frequency range in which the approximation will take place. By reducing the frequency range, the number of Debye poles needed for an adequate approximation is decreased, which subsequently results to an overall decrease of the computational requirements.

A number of authors have used multi-Debye functions in an effort to simulate simple homogenous soils [50]–[55]. Although, these approaches simulate the dielectric properties of the specific soils correctly, the use of homogenous models is still an oversimplification. A more inclusive approach is needed if different types of soils are to be modelled. In the present work, we use the semi-empirical model initially suggested by [56] and later modified by [57] and [58]. This semi-empirical model relates the dielectric properties of the soil to its bulk density, sand particles density, soil fraction, clay fraction and water volumetric fraction. The semi-empirical model resembles the Cole-Cole relaxation and can be easily approximated by a multi-Debye expansion. Using this approach a wide range of diverse soils can be incorporated into the model, as well as complex media with realistic statistical

variation of properties like water fraction, clay fraction and so on.

Rough surface can have a significant affect to the overall performance of GPR [9], [59]. Thus, a realistic numerical model should include a representation of the roughness of soil's surface. Fractals can express the earths topography with representative detail [60] for a wide range of scales. Therefore, fractal correlated noise [61] was chosen to describe the stochastic nature of the soil's topography. Fractal correlated noise is also employed in an effort to describe the soil's inhomogeneity. There is evidence in the literature [62]–[65] that supports the premise that for the scales used in the simulations presented here, fractals give rise to semivariograms often encountered in real soils.

Vegetation is a very important feature considering the GPR frequency range employed in demining and should not be neglected neither just simply defined. Both grass and roots are realistically incorporated into the suggested modelling scheme and simulated results indicate that they could have an effect on the overall performance of GPR. A novel algorithm is proposed that generates the geometry of both grass and roots with representative detail. The suggested algorithm creates the geometry of vegetation automatically having as its inputs statistical characteristics like grass distribution, maximum height of grass blades, maximum depth of roots, standard deviation of grass height, standard deviation of the maximum depth of roots and properties related to the shape of the grass and roots. Regarding the dielectric properties of vegetation, a multi-Debye expansion is used to approximate the function suggested in [66], [67]. The latter, relates the complex electrical permittivity of vegetation with its water weight based fraction. Water puddles are also incorporated into the numerical scheme in an attempt to simulate more humid environments.

Numerical modelling has been widely used for designing and optimising antennas. From complex antennas [68], [69] to more common designs such are: bowties [70]–[72], dipoles [73], vee dipoles [74], spiral [75] and horn antennas [76]. In addition, FDTD has been successfully employed to model generic types of antennas based on generic designs used in commercial ones [77]–[79]. In the present work, we use models of generic bowtie high frequency GPR transducers based on the geometrical characteristics obtained from commercially available antennas like the GSSI 1.5 GHz and the MALA 1.2 GHz as presented in [77]. Both of these GPR antennas are designed mostly for engineering applications but because of their high frequency range and their availability for simple testing have been chosen to illustrate the effectiveness of the proposed modelling framework for landmine detection.

The targets used in the simulations are detailed representations of the AP landmines PMA-1 and PMN. Dummy landmines have been used to obtain their geometrical characteristics. The dielectric properties of the AP landmines have been chosen from an iterative process of matching numerical and laboratory measurements of scattered electromagnetic fields in free space.

II. SOIL MODELLING

Soil modelling consists of two parts, the first part addresses the dielectric properties of the soil and the second deals with the soil's geometrical characteristics, *i.e.* the soil's inhomogeneity and rough surface.

A. Dielectric properties of the soil

In this work, a semi-empirical model – initially suggested in [56] – is used to describe the dielectric properties of the soil. This semi-empirical model relates the soil's relative permittivity to simply determined properties, namely, bulk density, sand particles density, sand fraction, clay fraction and water volumetric fraction. Using this approach, a realistic soil with a stochastic distribution of the aforementioned parameters can be modelled.

The semi-empirical model was originally suggested for the frequency range of 1.4 to 18 GHz [56]. Used in that form and for frequencies below 1.4 GHz it underestimates ϵ' and overestimates ϵ'' [57], [58]. Therefore, a modification was introduced in [57] and [58] for the frequency range of 0.3 to 1.3 GHz. In our proposed modelling framework, the dielectric mixing model is chosen based on the central frequency of the excitation pulse. If the central frequency is below 1.4 GHz the model for 0.3 to 1.3 GHz [57], [58] is used otherwise the model suggested for 1.4 to 18 GHz [56] is employed. Both models are described by equations (1)-(9), where $\epsilon_m = \epsilon' - j\epsilon''$ is the complex electrical permittivity of the defined medium, j is the imaginary unit ($j = \sqrt{-1}$), m_u is the water volumetric fraction, ρ_s is the sand particles density (g/cm³), ρ_b is the bulk density of the soil (g/cm³), ϵ_s is the relative permittivity of the sand particles, $a = 0.65$ is an experimentally derived constant and S and C are the sand and clay fractions respectively. The complex dipolar relaxation of water is described by (7), where $t_{0,w} = 9.23$ ps is the relaxation time of the water, $\epsilon_{w,s} = 80.1$ and $\epsilon_{w,\infty} = 4.9$ are the relative electrical permittivity of the water for zero and infinity frequencies respectively [57]. The term σ_f is a linearly proportional term to the conductivity σ .

$$\epsilon'_{(1.4-18 \text{ GHz})} = \epsilon_0 \left(1 + \frac{\rho_b}{\rho_s} (\epsilon_s^a - 1) + m_u \beta' \epsilon_w^a - m_u \right)^{1/a} \quad (1)$$

$$\epsilon'_{(0.3-1.3 \text{ GHz})} = 1.15 \epsilon'_{(1.4-18 \text{ GHz})} - 0.68 \quad (2)$$

$$\epsilon'' = \epsilon_0 m_u^{\frac{\beta''}{a}} \left(\frac{\sigma_f (\rho_s - \rho_b)}{\omega \epsilon_0 \rho_s m_u} - \epsilon_w'' \right) \quad (3)$$

$$\epsilon_s = (1.01 + 0.44 \rho_s)^2 - 0.062 \quad (4)$$

$$\beta' = 1.2748 - 0.519S - 0.152C \quad (5)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C \quad (6)$$

$$\epsilon_w = \epsilon_{w,\infty} + \frac{\epsilon_{w,s} - \epsilon_{w,\infty}}{1 + j\omega t_{0,w}} \quad (7)$$

$$\sigma_{f(1.4-18 \text{ GHz})} = -1.645 + 1.939\rho_b - 2.25622S + 1.594C \quad (8)$$

$$\sigma_{f(0.3-1.3 \text{ GHz})} = 0.0467 + 0.2204\rho_b - 0.411S + 0.6614C. \quad (9)$$

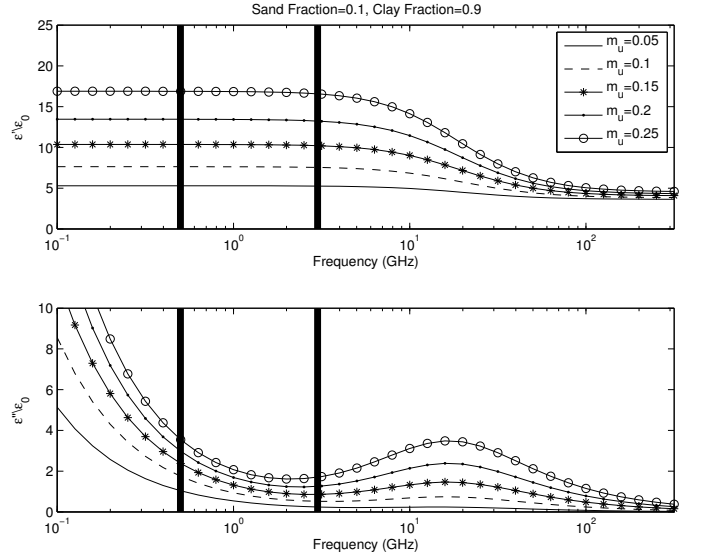


Fig. 1. Relative electrical permittivity for $\rho_s = 2.66$ g/cm³, $\rho_b = 2$ g/cm³, $S = 0.1$, $C = 0.9$ and for $m_u = 0.05 - 0.25$ with step 0.05. The frequency range of GPR for landmine detection is denoted between the bold lines.

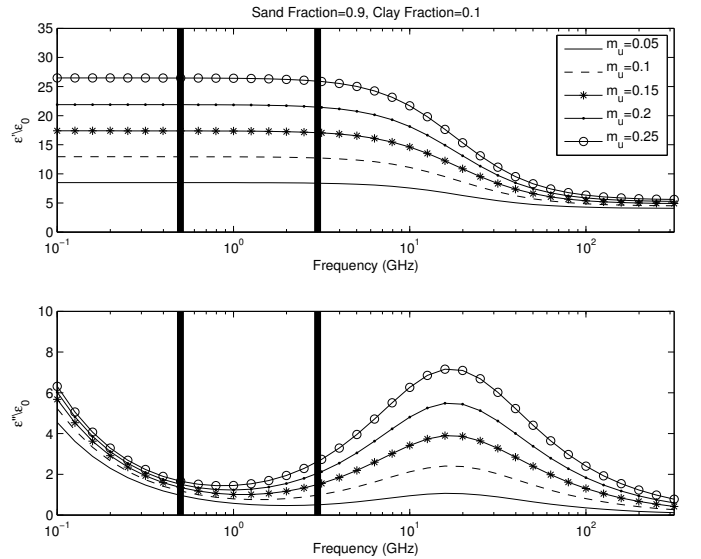


Fig. 2. Similar to Fig. 1 using $S = 0.1$ and $C = 0.9$.

Fig. 1 shows the relative electrical permittivity (using the model suggested for 0.3 to 1.3 GHz) for $\rho_s = 2.66$ g/cm³, $\rho_b = 2$ g/cm³, $S = 0.1$, $C = 0.9$ and for $m_u = 0.05 - 0.25$ with a step of 0.05. Fig. 2 is similar to Fig. 1 with $S = 0.9$ and $C = 0.1$. It is evident that the real part of the electrical permittivity, is practically constant over the frequency range of interest for landmine detection (0.5 to 3 GHz) and it increases when the volumetric water fraction is increased. Increasing the clay fraction results in the decrease of the real part of the electrical permittivity, *i.e.* increasing the velocity of the EM waves.

At first that seems not to be in good agreement with the general experience which expects low velocities in clay environments. This apparent peculiar result could be easily explained from the fact that clay environments (due to the

high porosity of clays) have usually significant water content that results to the decrease of their overall velocity. However, dry clay on the other hand has equal or even smaller real part of relative permittivity compared with dry sand [9]. Further, due to the high porosity of clays, dry clays could have a large fraction of air that adds to the overall increase of their velocity.

The imaginary part of the electrical permittivity consists of two parts, one related to the conductive term and one related to the Debye relaxation due to the water content (3). Increasing the water volumetric fraction results in an increase of the imaginary part (*i.e.* the attenuation) and also increases the contribution of the Debye relaxation. Increasing the clay fraction makes the electromagnetic losses to be primarily related to the conductive term and decreases the effects of the Debye relaxation at the frequency range used for landmine detection (0.5 to 3 GHz).

As the semi-empirical model cannot be directly implemented into FDTD a particle swarm optimisation (PSO) [80] has been used in order to approximate both the real and the imaginary part of the dielectric model explained in (1)-(9) with a conductive term plus a multi-pole Debye function (10),

$$\epsilon_m \approx \epsilon_\infty + \frac{\sigma}{j\omega} + \sum_{p=1}^N \frac{\Delta\epsilon_p}{1 + j\omega t_{0,p}} \quad (10)$$

where N is the number of the Debye poles and $\Delta\epsilon_p = \epsilon_{p,s} - \epsilon_{p,\infty}$.

In order for FDTD to be stable, $\Delta\epsilon_p$ must be positive and ϵ_∞ must be greater than ϵ_0 [46]. By increasing the number of Debye poles, the approximation becomes more accurate but for each extra Debye pole three additional memory variables are needed to be stored for each FDTD cell with dispersive dielectric properties. A balance between accuracy of the fit and computational cost must be achieved in order for the simulations to be both accurate and practical. For the frequency range of interest, a single Debye pole has been found to be an adequate approximation as it is shown at Fig. 3. Accurate approximations for wider range of frequencies require more Debye poles to be used subsequently increasing the computational requirements.

In order to illustrate the importance of implementing a realistic loss mechanism into the modelling scheme, a numerical experiment was performed using a simple 1D FDTD model. The model consists of four layers, namely air, soil, plastic and soil. The excitation is a Gaussian-modulated sinusoidal pulse with central frequency 2 of GHz. The relative electrical permittivity of plastic was chosen to be $\epsilon_p = 3$. Three different scenarios were tested. In the first one, a simple constant electrical permittivity is implemented without any losses. In the second one, a conductive term is added and in the third one, a Debye pole plus a conductive term are employed. The soil's properties are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 2 \text{ g/cm}^3$, $S = 0.9$, $C = 0.1$ and $m_u = 0.2$. Fig. 4 illustrates that the full Debye model with a conductive term apart from further decreasing the amplitude of the pulse, it also lowers the central frequency of the scattering field that subsequently reduces the ability of the pulse to resolve small targets. Electromagnetic losses can have a significant effect to the

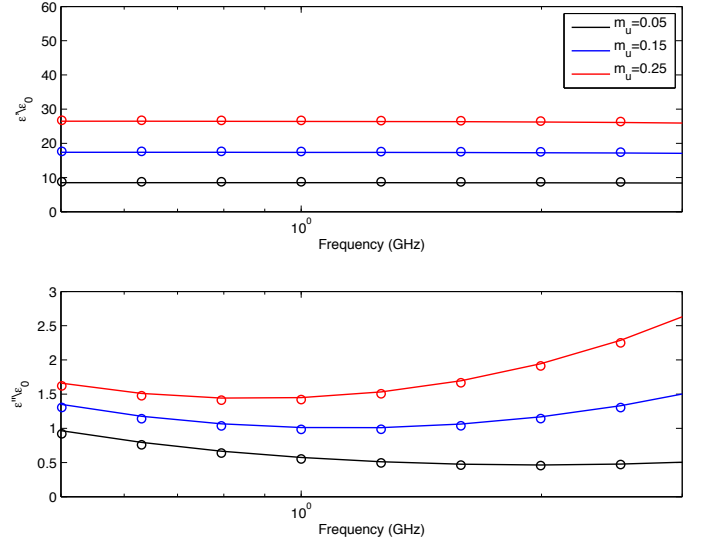


Fig. 3. The exact (lines) and the single pole Debye approximations (dots) of the relative electrical permittivity for the frequency range of interest (0.5 to 3 GHz). The properties of the soil are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 2 \text{ g/cm}^3$, $S = 0.9$, $C = 0.1$ and for $m_u = 0.05 - 0.25$ with step equals 0.1.

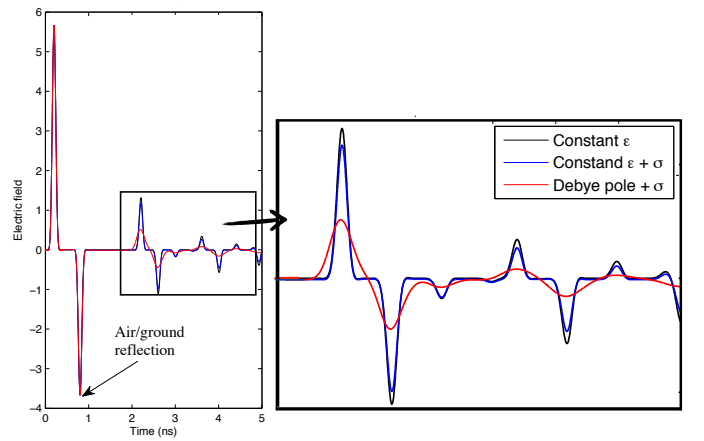


Fig. 4. Resulting scattering fields for a plane wave propagating in a four layer medium (air-soil-plastic-soil). Three different approaches are used for both soils to define their dielectric properties. With black, only a constant electrical permittivity is used. With blue, a constant electrical permittivity plus a conductive term is employed and with red, the full model (*i.e.* a Debye pole with a conductive term) is implemented.

overall signal to noise ratio as well as to the shape of the target's scattering field. From the above example it is evident that simple definitions of the loss mechanisms within the soil can result to a potential overestimation of GPR's performance. Thus, an accurate implementation of the dielectric properties is essential for a realistic numerical modelling scheme which aims to be used as a testbed for different processing algorithms or as a training platform for machine learning approaches.

B. Soil's geometrical characteristics

Fractals are scale invariant functions which can express the earth's topography for a wide range of scales with sufficient detail [60]. This is the reason why fractals were chosen in this work to represent the soil's topography. Fractals can

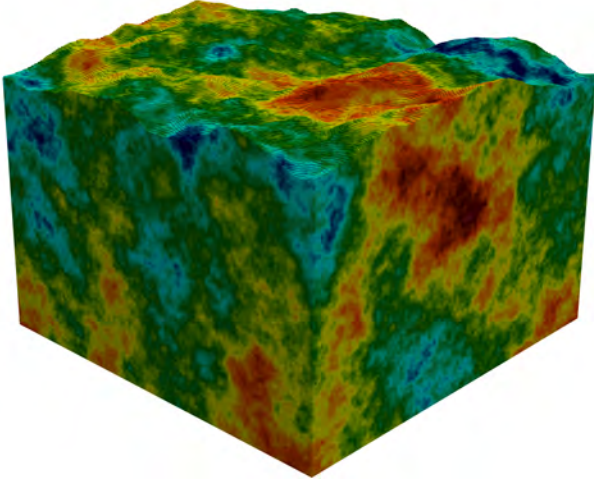


Fig. 5. Stochastic distribution of an arbitrarily chosen property of the soil (e.g. water volumetric fraction, clay fraction, sand density). The rough surface as well as the soil's property distribution is created using a fractal based approach.

be generated by the convolution of Gaussian noise with the inverse Fourier transform of $1/k^b$, where k is the wavenumber and b is a constant related with the fractal dimension [61]. Fig. 5 illustrates the resulting rough surface using fractal correlated noise. Increasing the fractal dimension results to the increase of the roughness of the soil's surface. The semivariogram (11) is a geostatistical tool used to describe correlation lengths and it is an attractive approach to describe the stochastic nature of soil's properties.

$$\gamma(h) = \frac{1}{2V} \sum_{i=1}^V |z(i+h) - z(i)|^2. \quad (11)$$

Where h is the lag distance, z is the investigated property (water fraction, clay fraction, bulk density etc.) and V is the number of the observations for each lag length (h). Soil's properties usually follow exponential, spherical or Gaussian semivariograms [62]–[64]. In this work, a fractal correlated noise [61] is used to describe the stochastic distribution of the soil's properties. This approach is chosen because as it is stated in [81], [82], soil-related environmental properties frequently obey fractal laws. Further, as it is shown in Fig. 6 the distribution of an arbitrarily property using 3D fractals results to Gaussian semivariograms for the scales used for AP landmine detection.

Fig. 5 illustrates an example of a stochastic soil's property distribution (e.g. water volumetric fraction, clay fraction, sand density etc.) and rough surface created using fractal correlated noise. Fig. 6 shows the simulated Gaussian and the calculated semivariogram for the model shown in Fig. 5. A Gaussian semivariogram can simulate the calculated one with sufficiently accuracy which is an indicator of the reliability of the modelled soil. Soil's inhomogeneity affect GPR's performance by decreasing the signal to noise ratio and by increasing the false alarm rate. A numerical scheme aiming to facilitate the development of processes to address such problems (through processing validation, antenna design, machine learning etc.)

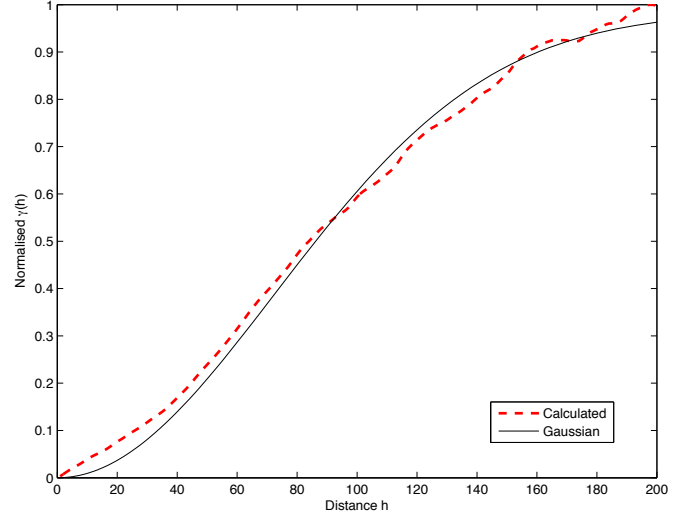


Fig. 6. Calculated semivariogram (dots) and simulated Gaussian semivariogram (solid line) of the arbitrarily chosen property of the soil shown in Fig. 5. The distance h is unit-less and represents the pixels in Fig. 5.

must be able to accurately simulate such negative effects. Modelling soil's inhomogeneity by using simple deterministic shapes and unrealistic property distributions may lead to data that are not suitable for machine learning purposes neither for evaluation of processing techniques.

III. VEGETATION

AP landmines are shallow buried targets, typically no more than 10 cm, and their diameter is usually 10 to 20 cm [3]. Therefore, in order for AP landmines to be detectable high frequency antennas are employed (0.5 to 3 GHz). The use of high frequency antennas leads to an increased sensitivity to small scale features such as grass and roots. In order to investigate the effects of vegetation to AP landmine detection using GPR, we propose an algorithm that models the geometrical characteristics of vegetation using statistical properties. The steps of the proposed algorithm are:

- A 2D fractal is created and the summation of the fractal values is constrained to be equal to one. Each fractal value represents the probability of a blade of grass to exist in the corresponding coordinates of this value (x_c, y_c).
- For each blade of grass, a maximum height is picked based on a Gaussian distribution.
- The parametric equations of each blade of grass are (for $0 < t < \text{maximum height}$):

$$x = x_c + s_x \left(\frac{t}{b_x} \right)^2 \quad (12)$$

$$y = y_c + s_y \left(\frac{t}{b_y} \right)^2 \quad (13)$$

$$z = t \quad (14)$$

where s_x and s_y can be 1 or -1 and they are randomly chosen. The constants b_x and b_y are random numbers based on a Gaussian distribution.

- For each blade of grass, a root is placed in the same coordinates (x_c, y_c) and a maximum depth for the root is picked based on a Gaussian distribution.
- The function which describes the geometry of the roots is a random walk in x and y coordinates as the depth increases linearly:

$$x_{i+1} = x_i + R_x \quad (15)$$

$$y_{i+1} = y_i + R_y \quad (16)$$

$$z_{i+1} = z_i - \Delta z \quad (17)$$

where both R_x and R_y are random variables based on a Gaussian distribution and Δz is the depth discretisation step. The iterative procedure described in (15)-(17) continues until z reaches the maximum depth of the root.

Dielectric models of plants like leaves of corn [83], stalks, trunks [84], [85] alfalfa [86], conifer trees [87] etc. have been reported in the literature. In the present work, the formula (18) suggested in [66], [67], is employed in an effort to describe the dielectric properties of vegetation

$$\epsilon'_g - j\epsilon''_g = 1.5 + \left(\frac{\epsilon'_w}{2} - j\frac{\epsilon''_w}{3} \right) M, \quad (18)$$

where ϵ'_w is the real part of the electrical permittivity of the water, ϵ''_w is the imaginary part of the permittivity of the water, j is the imaginary unit ($j = \sqrt{-1}$) and M is the water content based on a weight basis [67].

The main drawback of this model is that it is validated only to a single frequency of 8.5 GHz. Extending (18) to the wider frequency range of interest (0.5 to 3 GHz) results to an electrical permittivity which has a constant real part and an imaginary part which increases linearly with the frequency. This seems reasonable, but as it is reported in [67], the extension of this model to other frequencies should be checked experimentally.

Similar to soil modelling, a PSO is used [80] to simulate equation (18) with a multi-Debye function (10). For the frequency range of interest, a single Debye pole can sufficiently approximate equation (18) for different water weight based fractions (M) as it is shown in Fig. 7.

IV. ANTENNAS AND LANDMINES

The GPR transducers used in this work are models of bowtie antennas based on the geometrical characteristics of commercial GPR antennas namely, the GSSI 1.5 GHz and the MALA 1.2 GHz [77], [78] (see Fig. 8). Using realistic models of GPR antennas, is a reliable way to illustrate the capabilities of the proposed numerical scheme. When information is provided by manufacturers and antenna developers complex antennas can be accurately modelled and directly evaluated in realistic scenarios. Furthermore, bowtie antennas have been successfully applied for landmine detection [8] and have been also employed in previous published numerical schemes focusing on landmine detection [35], [37].

The targets employed in the simulations are the AP landmines PMA-1 and PMN. Both of them are widely used and frequently found in minefields [88], [89]. PMA-1 is a blast AP

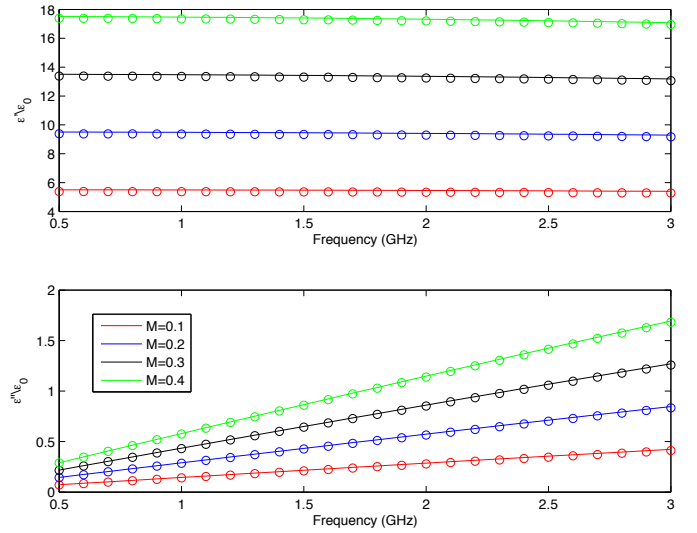


Fig. 7. Debye approximations (dots) compared with the analytic (lines) relative electrical permittivity of vegetation (18) for water weight fraction $M = 0.1 - 0.4$ with step 0.1.

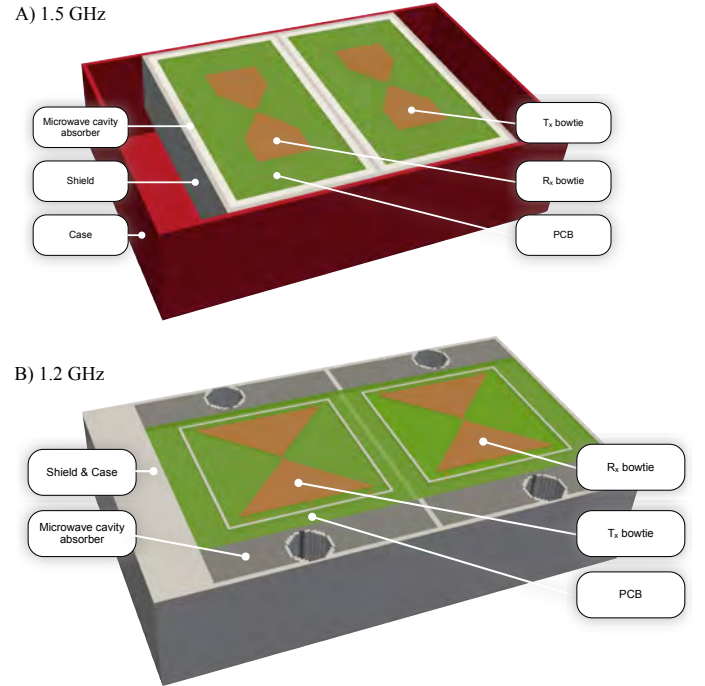


Fig. 8. Modelled antennas, A) 1.5 GHz and B) 1.2 GHz [77].

landmine with minimum metal content. It was manufactured in former Yugoslavia and was used in the Balkan area [89]. Because of the metal fuse inside PMA-1, it is possible to be detected with metal detector, but there are also reported types of PMA-1 with plastic fuses. PMA-1 has 200 g of high explosive content (TNT). The dimensions of PMA-1 are: height 30 mm, length 140 mm, width 65 mm. Fig. 9 illustrates the modelled AP landmine. The discretisation step used for the model is $\Delta x = \Delta y = \Delta z = 1$ mm. Larger discretisation step can be applied in a straightforward manner with a simple interpolation. PMN is one of the oldest landmines that are



Fig. 9. Modelled AP landmine PMA-1. Green is plastic ($\epsilon = 2.5$), grey is perfect conductor (PEC) and yellow is rubber ($\epsilon = 6$).



Fig. 10. Modelled AP landmine PMN. The adapted side parts of the landmine are shown at the right of the image. The black top of the AP landmine is rubber ($\epsilon = 6$), the black pieces on the adapted parts is bakelite ($\epsilon = 3.5$), shiny grey is perfect conductor (PEC), blue is plastic ($\epsilon = 3$), the grey parts of the landmine is also bakelite ($\epsilon = 3.5$) and the inside of the landmine is rubber ($\epsilon = 6$).

still in use. It is manufactured in Russia and it is one of the most widely employed landmines [88]. Similarly to PMA-1, PMN has a large amount of high explosive (240 g TNT). PMN is a palm shaped cylindrical blast AP landmine. It has a minimum metal content which can make the PMN detectable with metal detectors. The dimensions of PMN are: height 50 mm and diameter 115 mm. Fig. 10 shows the modelled PMN, the discretisation of the model is $\Delta x = \Delta y = \Delta z = 1$ mm. The dielectric properties of the modelled AP landmines are chosen such as the numerical and the real A-Scans from the experiment shown in Fig. 11 were in good agreement. During the experiment both of the AP landmines were placed over a perfect electrical conductor (PEC) and the antenna was positioned at 10 cm above the PEC. The antenna unit chosen for the experiment was the 1.5 GHz antenna. Fig. 12 illustrates that the numerical and the real normalised A-Scans are in good agreement which indicates the accuracy of the modelled AP landmines.

V. SIMULATION RESULTS

For the simulations we used gprMax [18], a free software that solves Maxwell's equations using a second order accurate FDTD method [19]. In all of the models, the discretisation step was set to $\Delta x = \Delta y = \Delta z = 1$ mm and the time step was equal to the Courant limit for the 3D FDTD scheme ($\Delta t = 1.925$ ps) [15]. A small discretisation step increases the computational cost but is essential in order to model the geometry of soil, targets, vegetation and antennas with very good resolution. In addition, a small discretisation step tackles the unnatural dispersion which occurs to small wavelengths due to numerical errors inherent in the FDTD [15]. Regarding the absorbing boundary conditions, a perfectly matched layer

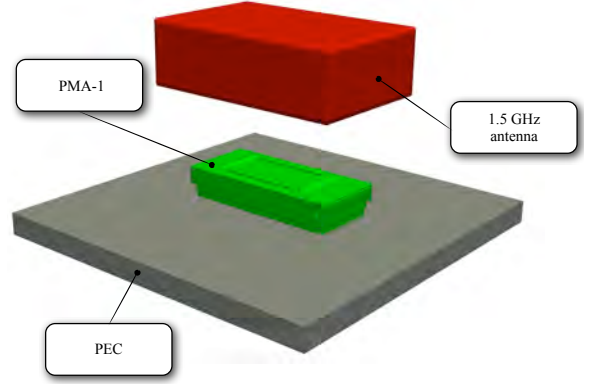


Fig. 11. The 1.5 GHz antenna (red box) operates 10 cm above a perfect electrical conductor (PEC) on which the PMA-1 is placed. The same experiment was also executed using the PMN.

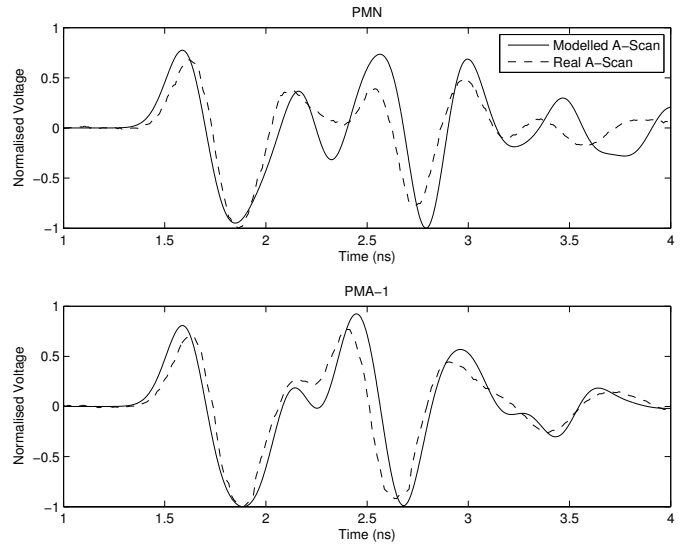


Fig. 12. Numerical and real normalised A-Scans for the experiment described in Fig. 11 using both PMA-1 and PMN.

(PML) [15], [90] with 10 cells thickness is applied to all the simulations.

The computational requirements are related to the model's size, its dielectric properties and the maximum number of iterations required for a given GPR time window. Dispersive soils have increased computational requirements compared to non-dispersive media. In that context, a $1000 \times 400 \times 300$ (cells) model consisted entirely of dispersive media needs approximately 8 gigabyte of Random-Access Memory (RAM). Using 6 processors and 12 gigabyte of RAM, the computation time for such a model was approximately 2 hours per trace for 2500 iterations.

The computational resources required for these kind of modelling problems are more than what a conventional computer can offer if results are to be obtained in reasonable time. To overcome this obstacle we have employed ECDF [91], the cluster computer of The University of Edinburgh. A parallelised version of gprMax has allowed us to compute complete B-Scans in the same time that was needed for

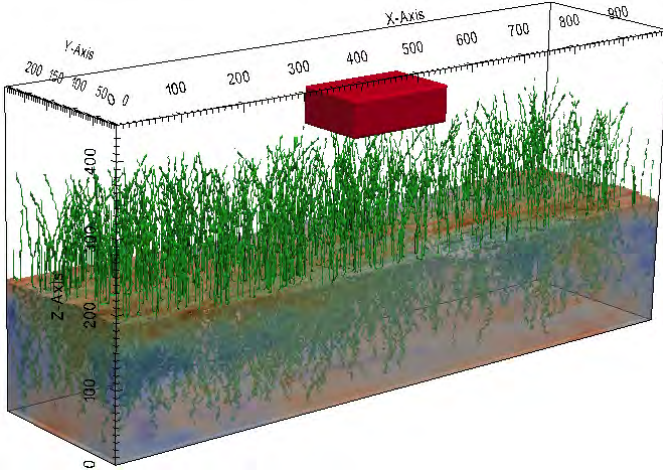


Fig. 13. AP landmines PMN and PMA-1 buried in a soil with stochastic varied water volumetric fraction from $m_u = 0 - 0.25$. Red colours depict the dry areas while with blue colours saturated areas are illustrated. The red box is the antenna unit. The axis are in mm.

computing a single A-Scan on a single workstation.

A. Vegetation

In the first example we examine how vegetation affects landmine detection using GPR. The model's dimensions are $1000 \times 250 \times 450$ mm, the surface is relatively smooth, the soil's properties are $\rho_s = 2.66$ g/cm³, $\rho_b = 2$ g/cm³, $C = 0.5$, $S = 0.5$ and the water volumetric fraction varies stochastically from $m_u = 0$ to 0.25 . The height of grass blades varies from 20 to 130 mm and the roots from 20 to 200 mm. Three different scenarios were tested with both antenna models. In the first scenario, the water weight based fraction of the vegetation is equal to $M = 0.4$ (saturated grass and roots). In the second scenario, the water weight based fraction is $M = 0.1$ (dry grass and roots) and in the third scenario there is no vegetation. Fig. 13 and 14 illustrate the geometry of the model. The height of the antenna unit is approximately 160 mm above the ground and 20 mm above the grass. The depth of both landmines is approximately 50 – 70 mm. The B-Scan is taken place along the x axis. The moving step of the antenna is 6 mm which results to a B-Scan consisted of 132 traces. To all the simulations presented in this subsection a quadratic gain and subsequently a singular value decomposition (SVD) [92], having three dominant eigenvalues filtered out, are applied to the raw data. After removing the ground clutter and the ringing noise, the energy of each trace is calculated by (19)

$$P(x) = \int_0^\infty E_y(x, t)^2 dt. \quad (19)$$

Fig. 15 presents the B-Scans and normalised energy plots for the present model (see Fig. 13 and 14) using the 1.5 GHz antenna. In the absence of vegetation, both AP landmines can be reliably detected from the B-Scans and the energy plots. When vegetation is present and as the water weight based fraction increases, B-Scans as well as energy plots become noisy and more difficult to interpret. This is due to the high frequency content of the antenna (1.5 GHz) which results to

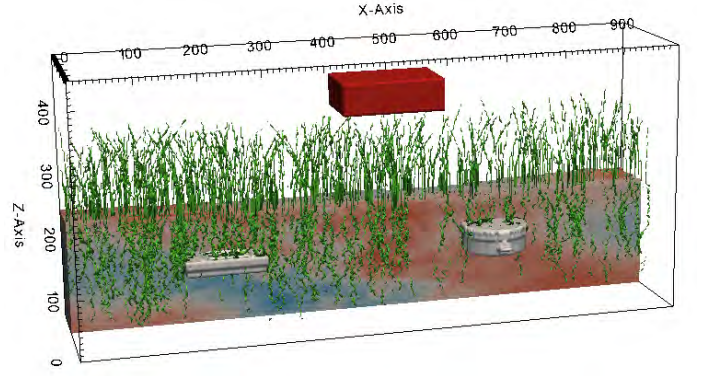


Fig. 14. A slice parallel to the tomography line of the model shown in Fig. 13.

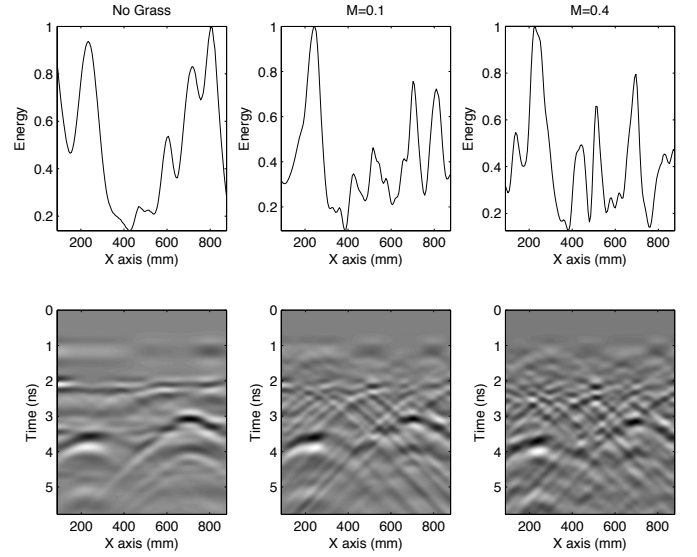


Fig. 15. B-Scans and normalised energies of the model shown in Fig. 13 with and without vegetation. The vegetation's water weight based fraction equals $M = 0.1$ and $M = 0.4$. The 1.5 GHz antenna is used in the simulations. A quadratic gain and subsequently a singular value decomposition (three dominant eigenvalues are filtered out) are applied to the raw data. The X axis corresponds to the center of the antenna unit in each trace.

an increased sensitivity to features such as vegetation. Using a higher frequency antenna will further increase this problem. Using the 1.2 GHz antenna, due to the slightly lower frequency content of the pulse, the effects of vegetation are not as dominant. However vegetation can result to false alarms as it is shown in Fig. 16 for $M = 0.1$. The present case study shows that the simulated vegetation is not a negligible feature and it can potentially affect the performance of GPR for the frequency range used for landmine detection. Nonetheless, Fig. 15 and 16 illustrate that GPR has the potential to be effective in grassy environments in which vegetation removal is not trivial due to tripwires that might be present [3].

B. Soil's inhomogeneity

Apart from vegetation, more frequently-encountered features like soil's inhomogeneity can also result to false alarms and mask the landmine's scattering field [93]. Most of the

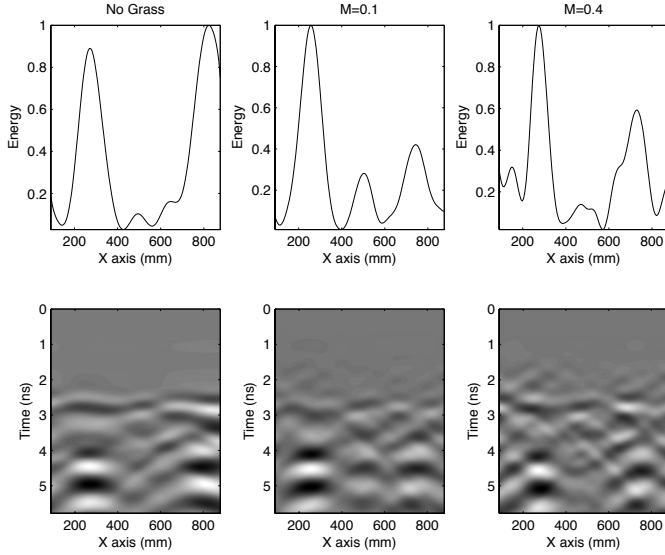


Fig. 16. Similar to Fig. 15 using the 1.2 GHz antenna.

numerical modelling done so far, as well as some real field experiments took place in simplified/clinical settings. This overestimates the performance of GPR and gives often a false impression regarding its abilities and its limitations. The dimensions of the models in this section are $1000 \times 250 \times 350$. The properties of the soil are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 1.5 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and the water volumetric fraction varies from $m_w = 0$ to 0.25 . The model antenna used was the 1.5 GHz and it is placed relatively close to the ground. Two cases are presented, in the first one the AP landmine PMA-1 is placed at the centre of the model at approximately 40 mm depth from the surface. In the second example no landmines are present in an effort to put the emphasis on the level of the resulting clutter (see Fig. 17). Figure 18 presents the resulting B-Scans using the 1.5 GHz antenna. A quadratic gain is initially applied to the raw data. Subsequently three different processing methods were used: a high pass filter, an Adaptive Scaled and Shifted (ASaS) method [94], [95] and an SVD filtering out three dominant eigenvalues. It is evident that the landmine's signature is masked from the ground clutter (low signal to noise ratio). In addition, the soil's inhomogeneity can give rise to false alarms as a result of the presence of inhomogeneous clusters in the ground. From the above, it is concluded that soil's inhomogeneity is an essential feature for a realistic and useful numerical modelling framework aiming to reliably assist in evaluating a GPR's performance. Realistic and complex B-Scans from high clutter environments can provide a challenging testbed for evaluating as well as comparing different processing approaches and antenna designs.

C. Targets

Different targets give rise to different scattered signatures. For high frequency problems like GPR for AP landmine detection, detailed modelling of the targets of interest is a basic requirement if, for example, the numerical scheme is to be

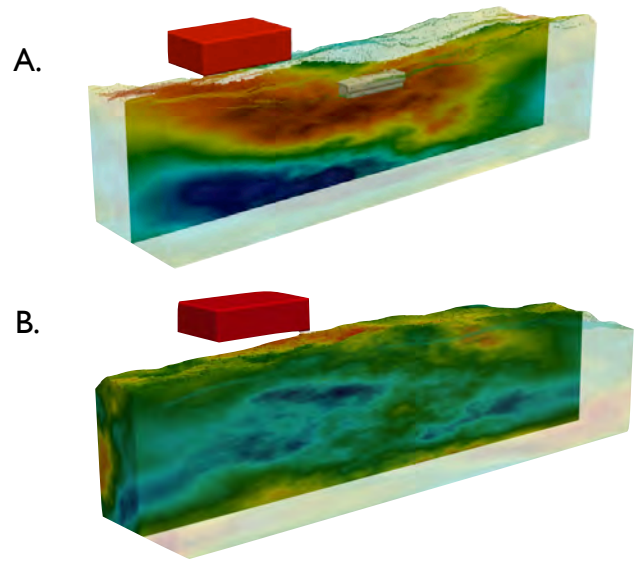


Fig. 17. A) Buried AP landmine PMA-1 in a stochastically varied soil. B) No landmine is buried in order to get an insight on the resulting clutter. The properties of the soil (for both cases) are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 1.5 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and water volumetric fraction which varies from $m_w = 0 - 0.25$. The antenna unit used is the 1.5 GHz.

used as a training platform for machine learning. In the present section, the importance of accurate models of landmines is illustrated. The two AP landmines PMN and PMA-1 are buried in the same stochastically varied soil (see Fig. 19) in an effort to illustrate the different resulting B-Scans. The dimensions of the models in this section are $1000 \times 250 \times 350$. The rough surface as well as the soil's inhomogeneity are modelled using fractal correlated noise. The properties of the soil are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 1.5 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and the water volumetric fraction varies from $m_w = 0$ to 0.25 . The model antenna unit used was the 1.5 GHz and it was placed relatively close to the ground. Fig. 20 clearly illustrates the differences between the two B-Scans (a quadratic gain and a high pass filter is applied for both cases). From this is clear that a numerical scheme that potentially can be used to provide training sets for machine learning should be able to predict the signatures of specific landmines and not generic simplified geometrical objects.

D. Water puddles

AP landmines can be found in a variety of environments [10]. Humid environments with saturated soils and water puddles is a common environment in which AP landmines can be found (*e.g.* Bosnia, Cambodia etc. [10]). In this section we will briefly examine how water puddles can affect the performance of GPR for AP landmine detection.

The dimensions of the models are $1000 \times 250 \times 450 \text{ mm}$, the modelled antennas are placed close to the ground surface (40 mm) and the AP landmines are buried at 60 mm depth. The soil is a homogenous saturated sand with $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 2 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and $m_u = 0.15$. Three different scenarios are examined in which water puddles are gradually increased (see Fig. 21). The complex relative

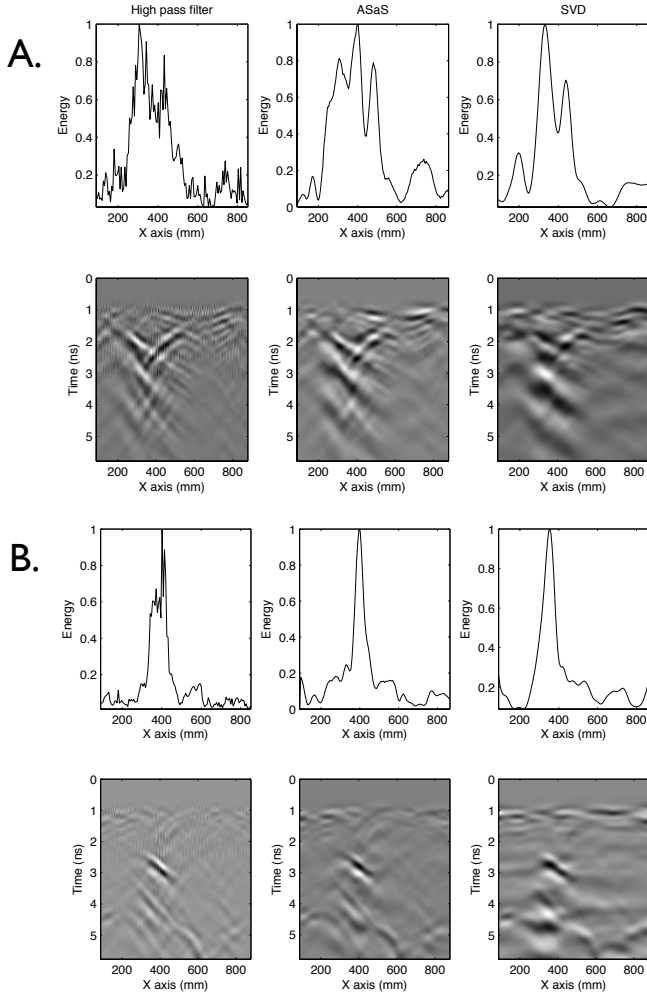


Fig. 18. B-Scans using the 1.5 GHz antenna for the models illustrated in Fig. 17. A high pass filter, ASaS and an SVD (3 dominant eigenvalues are filtered out) are applied subject to a quadratic gain.

electrical permittivity of water is a Debye function (10) with $t_{0,w} = 5.8$ ps, $\epsilon_{w,s} = 80.1$ and $\epsilon_{w,\infty} = 4.9$ [56]. Notice that only the dipolar relaxation of the water is used in the simulations. The conductive term which is related to the salinity of water [96] is neglected. This is due to the fact that water puddles mostly consist of fresh water for which the main loss mechanism is the dipolar relaxation. If high-salinity water needs to be modelled, the formula suggested by [96] can be used in order to express conductivity with respect to temperature and particles per thousands (ppt). Subsequently the conductive term can be easily implemented in FDTD. Fig. 22 and 23 illustrate both B-Scans and energy plots using the 1.5 GHz and the 1.2 GHz antenna respectively. A quadratic gain is applied to the resulting B-Scans using both antennas. An average removal technique [92] is proven to give good results for the 1.5 GHz but doesn't perform equally well when the 1.2 GHz antenna is employed. Due to that a high pass filter is applied to the B-Scan obtained when using the 1.2 GHz antenna and an average removal is used for the 1.5 GHz antenna. Increasing the size of the water puddles decrease the quality of the results when using the 1.2 GHz antenna

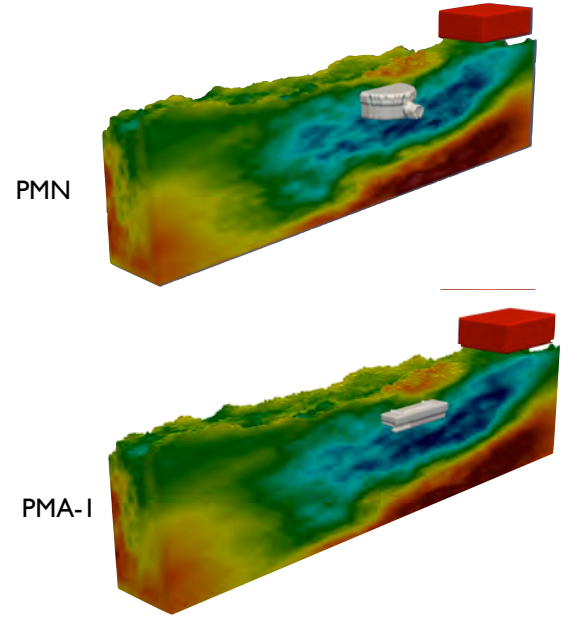


Fig. 19. Buried AP landmines PMA-1 and PMN in a stochastically varied soil. The properties of the soil are $\rho_s = 2.66$ g/cm³, $\rho_b = 1.5$ g/cm³, $C = 0.5$, $S = 0.5$ and water volumetric fraction which varies from $m_w = 0 - 0.25$. The antenna unit used is the 1.5 GHz.

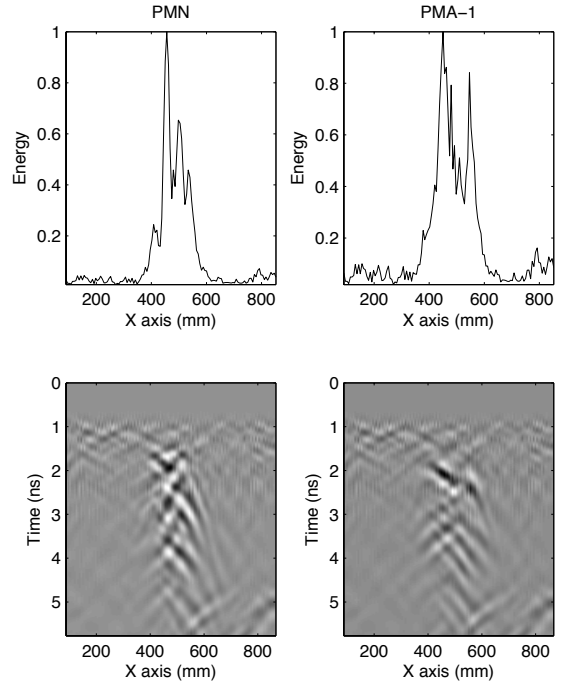


Fig. 20. B-Scans using the 1.5 GHz antenna for the models illustrated in Fig. 19. A quadratic gain and a high pass filter are applied to the raw data.

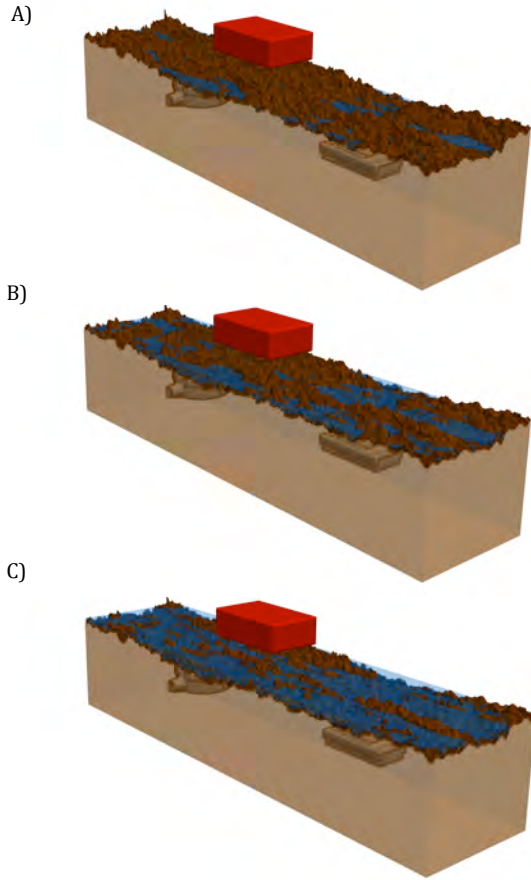


Fig. 21. Water puddles with gradually increasing size over a homogenous saturated sand with fractal rough surface. The soil's properties are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 2 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and $m_u = 0.15$.

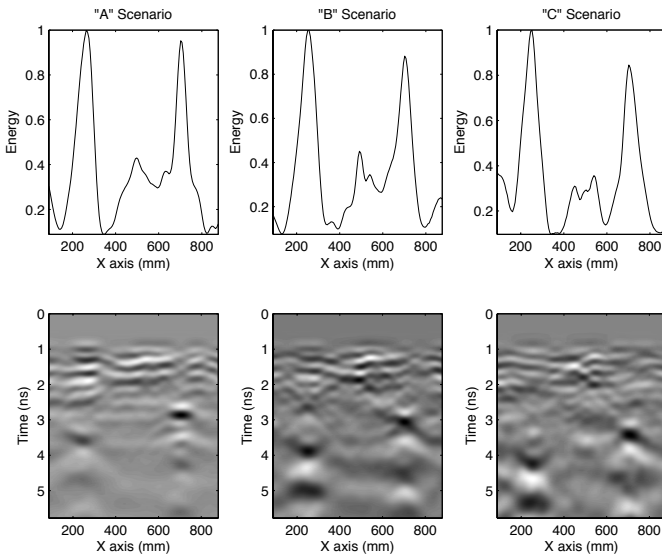


Fig. 22. B-Scans of the models shown in Fig. 21 using the 1.5 GHz antenna. "A", "B" and "C" scenario corresponds to the gradual increase of the water puddles. A quadratic gain and subsequently an average removal technique, are applied to the raw data. The X axis corresponds to the center of the antenna unit.

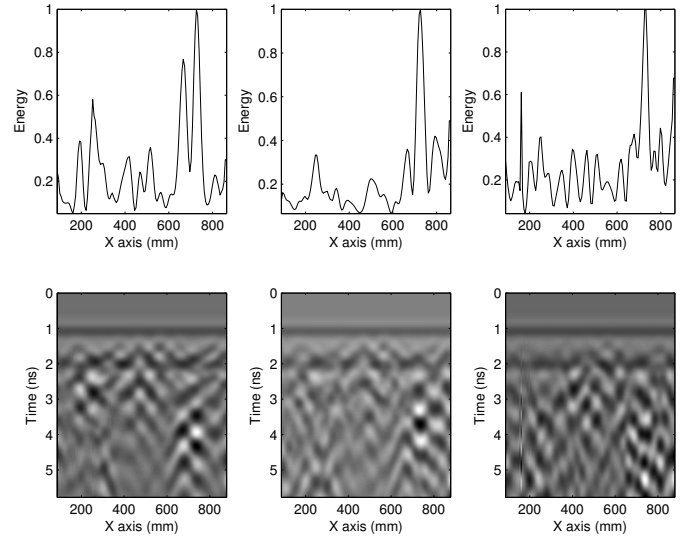


Fig. 23. Similar to Fig. 22 using the 1.2 GHz antenna. Instead of average removal a high pass filter is applied.

Increasing the size of the water puddles in "C" scenario makes the detection of PMN difficult and unreliable (Fig. 23). PMA-1, using the 1.2 GHz antenna (for all the three scenarios) results in weak scattering signals (compared to clutter) which are unreliable for interpretation (Fig. 23). The reasons why PMN is easier to be detected compared with PMA-1 is because more water puddles occur above PMA-1 and because PMN is a bigger target therefore easier to be resolved by the incident pulse. Due to the high dipolar losses of the water, no multi-interference phenomena neither waveguide effects occur within the water. The high frequency propagating modes of a thin dielectric slab (like water puddles) are rapidly attenuating due to water's dipolar losses.

From Figs. 22 and 23 is evident that the 1.5 GHz antenna gives clearer results with respect to the 1.2 GHz one. The reason for that is because the high frequency content which is essential in order to get a clear reflection from the AP landmines, which are small targets, is rapidly attenuating inside the water and the saturated sand. The 1.2 GHz antenna has a lower frequency content which manages to pass through the water but it cannot resolve well the AP landmines. The already lower high frequency content of the 1.2 GHz antenna is attenuated inside the water, due to that, the pulse that finally reaches the AP landmines has a rather lower central frequency that makes the AP landmines undetectable. This is the reason why high pass filtering works better than the average removal processing using the 1.2 GHz antenna (*i.e.* it enhances the high frequency content of the B-Scan). On the other hand the 1.5 GHz antenna has a larger amount of high frequency content that manages to pass through the water and get a clear reflection from the AP landmines. The reduction of the central frequency of the pulse due to the water puddles is illustrated in Fig. 22. In all the scenarios ("A", "B" and "C") the early reflections from the surface have a higher frequency content compared with the later reflections from the AP landmines. As the size of the water puddles increase the frequency content

(Fig. 23). In "A" and "B" scenario the PMN is detectable.

of the resulting scattering fields from the AP landmines is decreased. This is also due to the Debye pole which describes the dielectric properties of the saturated sand.

E. Water puddles and vegetation.

In this last section we examine how the combination of rough surface, water puddles and vegetation affects the simulated GPR performance for AP landmine detection. Three different cases are examined in which, rough surface, water puddles and vegetation are implemented into the models. The dimensions of the model are $1000 \times 250 \times 450$ mm, the properties of the soil are $\rho_s = 2.66 \text{ g/cm}^3$, $\rho_b = 2 \text{ g/cm}^3$, $C = 0.5$, $S = 0.5$ and the water volumetric fraction varies stochastically from $m_u = 0$ to 0.25 . The water weight based fraction of the vegetation is equal $M = 0.4$. In the first case, the AP landmine PMA-1 is buried in the center of the model at 60 mm depth, in the second case, AP landmine PMN is buried in the centre of the model also at 60 mm depth and in the third case, no landmines are present in order to investigate the false alarms which might occur (Fig. 24). One interpretation of these examples is to assume that they do resemble a tropical-humid environment in which AP landmines are frequently found (PMN has been extensively used at the Thai border [88] in heavily vegetated jungle environments). As AP landmines can be found in a wide range of environments, from arid to tropical [9] a efficient numerical scheme should be capable of addressing the issue of diversity and not be constrained to specific cases.

Fig. 25 and 26 illustrate the B-Scans and the energy plots using the 1.5 GHz and the 1.2 GHz antenna models respectively. A quadratic gain and an SVD having four dominant eigenvalues filtered out, are applied to the raw data. Using both antenna models results to noisy and difficult to interpret B-scans. The 1.2 GHz antenna gives indications of PMN and PMA-1 but similar patterns also occur in the case of no landmines. This increases the false alarm rate to a level that demining could become more difficult and rather time consuming. Using different processing algorithms (e.g. SVD filtering out different eigenvalues, average removal technique, high pass filter, adaptive ground removal [94], [95]) leads to equally unreliable results. This clearly illustrates the difficulties that GPR has in some truly complex environments. It is evident from these examples that a numerical scheme that aims to be used as a testbed for developing GPR antennas and advanced processing methods should be capable of producing difficult and challenging data sets. Previous approaches [31]–[37] often resulted in rather clinical B-Scans that were easy to be addressed using trivial processing methods.

VI. CONCLUSIONS

A systematic framework for accurate and realistic numerical modelling of ground penetrating radar for landmine detection has been introduced. Methods for implementing both the dielectric properties and the geometrical characteristics of the subsurface were proposed as well as methods for implementing vegetation into the models. The effects of vegetation, water puddles, rough surface and complex soils were examined and

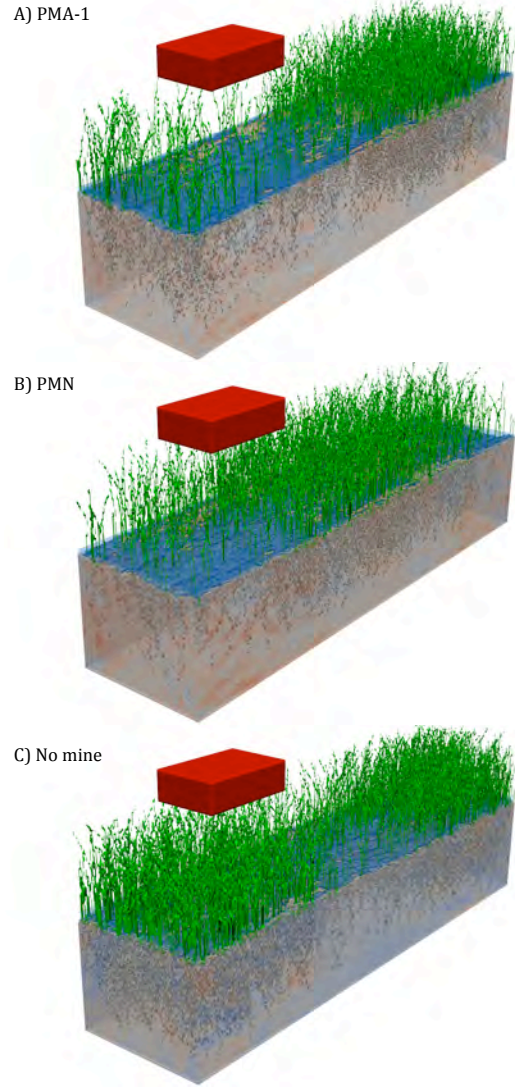


Fig. 24. Three different complex media with a stochastically varied water volumetric fraction, rough surface, water puddles and vegetation. In case “A”, the AP landmine PMA-1 is buried at the centre of the model at approximately 60 mm depth. In case “B”, PMN is placed 60 mm (approximately) beneath the ground surface and in “C”, no landmines are present.

cases shown for which GPR – using the specific modelled antennas – has difficulties in clearly and easily detecting the simulated AP landmines. This is in contrast to results from more clinical and simplified models in which numerical GPR modelling gives usually clear and predictable results. Therefore, it appears that realistic simulation results can more consistently predict the GPR’s behaviour in a manner that is closer to the experience of using GPR in the field.

The overall aim of this work was to investigate the possibility of modelling GPR for landmine detection as much as realistically as possible. The availability of such a detailed numerical modelling framework allows us to investigate in the future advanced processing algorithms and new interpretation schemes without having to oversimplify the problem that often produces predictable outcomes and lead to approaches that as seen in practice do not always perform well in the field.

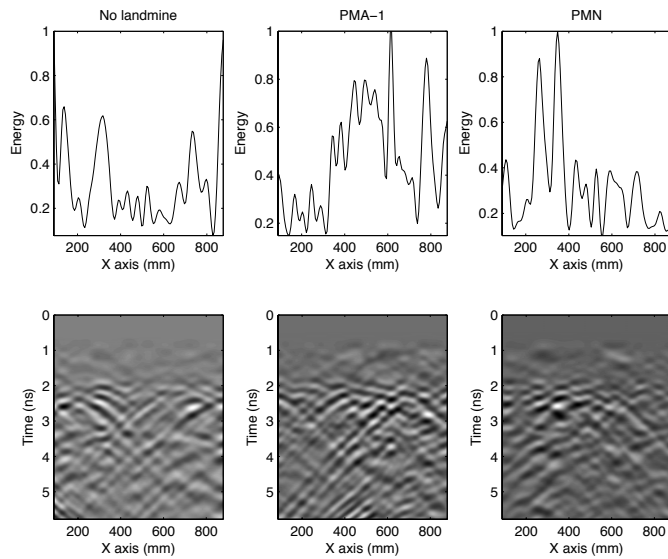


Fig. 25. B-Scans and energy plots using the 1.5 GHz antenna for the cases shown in Fig. 24. A quadratic gain and subsequently a singular value decomposition (four dominant eigenvalues are filtered out) are applied to the raw data. The X axis corresponds to the centre of the antenna unit.

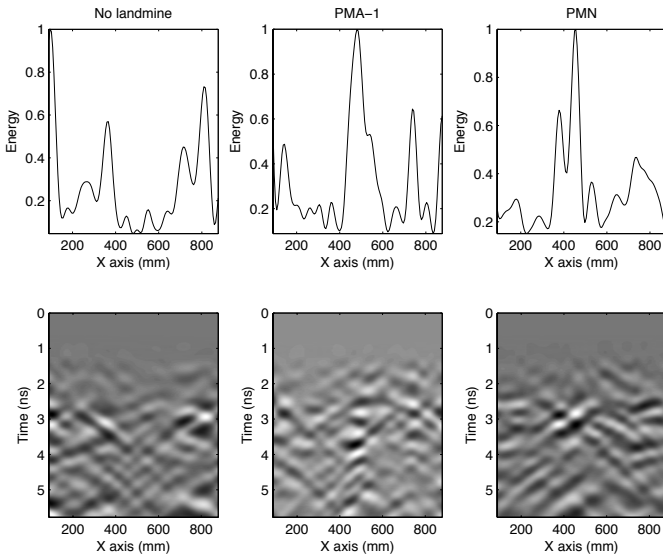


Fig. 26. Same with Fig. 25 using the 1.2 GHz antenna.

Extensive field testing is obviously the only viable route to be certain that a new approach could be beneficial. However, such a realistic modelling framework is valuable in the phase of developing and testing ideas. Finally, it has also been illustrated via the numerical modelling examples, that processing methods are often case sensitive. As a result, interpretation methods must be validated using a diverse set of scenarios. A realistic numerical model is a practical and efficient way to address this issue by providing synthetic but nonetheless realistic data. The long term intention of this modelling work is to inform and support GPR antenna design, provide a reliable testbed for developing advanced signal processing approaches and used as a training platform for machine learning purposes.

ACKNOWLEDGMENT

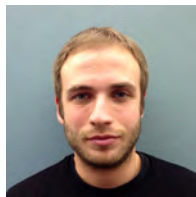
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